OPTIMIZATION METHOD FOR
POWER GENERATION SYSTEMS

RELATED APPLICATION

[0001]   This application is a continuation-in-part of Patent
Application No. 09/729,457 filed December 5, 2000, now U.S.
Patent No. 6,340,289, which is a continuation of Patent
Application No. 09/054,411 filed April 3, 1998, now U.S. Patent
6,171,055, and is incorporated herein by reference.

BACKGROUND OF THE INVENTION

1.   Field Of The Invention

[0002]   The present invention relates to method and apparatus
for controlling the output of a power generation system using a
single input power controller.

2. Related Background

[0003]   In the field of engine control, many proposals exist
for controlling the flow of fuel to the engine in accordance with
detected engine operating parameters such as engine temperature,
engine pressure ratio, shaft speed, etc. to maximize fuel
efficiency, but such proposals fail to take into account the
ambient operating conditions. Proposals of this type are
described in U.S. Patent Nos. 4,248,042; 4,551,972; 4,686,825;
5,029,778; 5,039,037; 5,277,024; and 5,613,652. However, even if
such systems were adapted to power generation systems such as
used by electric utilities, technicians would still be required
to operate and continually adjust a plurality of control levers
to optimize engine output for given environmental conditions.

[0004]   By 1985, it was recognized that aircraft engine
efficiency is highest when the engine is run with the throttle
butterfly valve fully open and the desired performance is
obtained by varying propeller speed. See, for example, SAE
Technical Paper Series 850895, The Porsche Aircraft Engine P F M
3200", Helmuth Bott and Heinz Dorsch, 1985. This article
proposed a single-lever control system for an aircraft engine
that operates both the throttle and the propeller governor with a
single lever. However, the proposed system is a mechanical
linkage system which accordingly cannot optimize engine
performance based on various ambient flight conditions. That is,
the Porsche system may work well at a single altitude, speed, and
temperature, but will seriously degrade at other flight
conditions.

[0005]   Similarly, it may be advantageous in a power generation system, to allow the prime mover or engine to operate at a full throttle condition, while manipulating the attached electrical generator and/or connecting gear box to achieve maximum efficiency based on current environmental parameters. This approach may also be applied to wind turbine applications as well as propulsion systems for ground vehicles.

SUMMARY OF THE INVENTION

[0006]   The present invention is intended to overcome the drawbacks of known power generation control systems by providing a processor-controlled system which inputs a single power command, receives detected ambient environmental conditions, and automatically controls the engine/generator output, and engine load (e.g., manifold air pressure (MAP)) for the detected environmental conditions relative to the requested power command.

[0007]   According to a first aspect of the present invention, a single input power control apparatus for controlling a power generation system includes a single, manually-operable input for generating a power level generation command. A processor receives the generated power level command, receives a plurality of detected ambient air conditions, and determines an engine speed activation command and an engine load activation command based on the maximum output power efficiency for the detected ambient environmental conditions and power level command. In one embodiment, the output power efficiency optimization is performed off-line where the processor accesses a look-up table which stores highest output power efficiency values for the detected

environmental conditions and power level command. In another
embodiment, the optimization is performed on-line where the
processor determines the highest output power efficiency values
by varying the existing values and determining any change in the
power output. A positive change indicates more efficient output
power values, and these will be used to control the engine.

[0008]   Similarly, according to a further aspect of the present
invention, control apparatus for use with a wind power generator
control device includes an electrical power generator connected
to a propeller of a wind turbine. A processor receives a
generated power level command, receives a plurality of detected
ambient air conditions, and determines a gear box speed
activation command and a propeller load activation command based
on the maximum output power efficiency for the detected ambient
environmental conditions and power level command. Output from
the wind turbine is automatically controlled by altering the
pitch of the turbine blades in accordance with the output of the
processor, thereby selecting the most efficient operating
condition for the wind turbine.

[0009]   According to another aspect of the present invention,
apparatus for controlling a ground vehicle engine having an
internal combustion engine and an air inlet includes a single,
manually-activated structure for providing an engine thrust
command such as an accelerator pedal or a remote command in the
case of an unmanned vehicle. A processor is provided for
receiving the engine output command and detected ambient air
conditions, and determines first and second control commands for
the engine. The processor determines the first and second

control commands based on the received engine output command, the detected ambient air conditions, and a maximum engine output efficiency value for the detected ambient air conditions.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010]   The novel structure and functions according to the present invention will become readily apparent to those of ordinary skill in the art from the following detailed description of the preferred embodiments taken together with the accompanying drawings which show:

[0011]   Figure 1 is a block diagram of the power generation structure according to one embodiment of the present invention;

[0012]   Figure 2 is a functional block diagram of the embodiment depicted in Fig. 1;

[0013]   Figures 3 is a block diagram of the wind turbine control structure according to another embodiment of the present invention;

[0014]   Figure 4 is a block diagram of another preferred embodiment directed at power generation systems for ground vehicles;

[0015]   Figure 5 is a contour map representing output power vs. MAP vs. RPM in accordance with the embodiment shown in FIG. 1;

[0016]   Figure 6 is a contour map showing constant output power in accordance with the embodiment shown in FIG. 1;

[0017]   Figure 7 is a graph showing the constrained maximum output power efficiency in accordance with the embodiment shown in FIG. 1.

DETAILED DESCRIPTION OF THE
PREFERRED EMBODIMENTS

1.   Introduction

[0018]   Power plants for power generation are typically comprised of a plurality of prime power sources such as turbine engines, gas powered internal combustion engines and the like each connected to a generator through a variable speed transmission/gear box. The engine burns fuel thereby converting the fuel into electrical energy that is in turn produced by the generator. The efficiency of the power generation system may be improved by monitoring environmental parameters and selecting setpoints for controlling engine speed and generator output based on the known performance of the system.

[0019]   Similarly, a wind turbine produces electrical energy by converting the energy in the wind into rotation of a propeller which is connected to an electrical generator by a variable speed transmission. Wind turbine power generators, however, do not always operate at maximum efficiency based on measurable environmental conditions and operating parameters. Overall wind turbine operating efficiency may be improved by monitoring the

environmental parameters and selecting setpoints of the wind turbine and the generator/gear box to provide maximum output power efficiency. Alternatively, if power shedding capabilities exist, the load on the generator may be varied to also maximize wind turbine efficiency.

[0020]   In yet another example of power generation, a prime mover such as an internal combustion engine is provided in a ground vehicle to transmit power to the wheels of the vehicle to move the vehicle along the ground at some desired speed. Overall prime mover efficiency may be improved by monitoring operating parameters such as transmission/wheel speed and engine speed to find the optimum operating setpoints for the engine and/or transmission.

[0021]   The present invention dovetails nicely with the advances recently made in electronic control of engine parameters such as fuel mixture, operating temperature, etc. Engine control units (ECU=s) and power plant control units (PCU's) are used in the automotive industry to digitally fine-tune fuel consumption in the power plant.

[0022]   While the present invention is described with respect to power generation systems such as wind turbines and ground vehicles, those skilled in the art will appreciate that other applications may include many other well known power generation systems.

2. <u>The Structure</u>

[0023]   Fig. 1 depicts the structure according to a preferred embodiment of the present invention in which prime power source 2 comprises a known prime power source for use in power generation stations, for example, a gas fired internal combustion engine, a high speed turbine engine or the like. An electrical generator 3 is connected to the prime power source 2 by a gear box 5. The gear box 5 may be a variable speed transmission that can be controlled by an output from the controller. Load 4 may comprise any known electrical power transmission means for transmission of the electrical power generated by the generator 3.

[0024]   Prime power source 2 has an intake manifold 10 and an exhaust manifold 12. The exhaust manifold 12 has two branches, a branch 14 which may provide output to an optional turbo charger (not shown), and a branch 16 which is vented to the atmosphere. An optional movable waste gate 18 controls the balance of exhaust gases between branch 14 and 16 so as to control the amount of exhaust gases provided to the turbo charger 14. A waste gate servo 20 controls the position of the waste gate valve 18 in accordance with feedback from the measured intake manifold pressure (to be described below).

[0025]   The intake manifold 10 has a movable throttle valve 22 which is controlled by a throttle servo 24. A manifold air pressure (MAP) sensor 26 detects the intake manifold air pressure.

[0026]   The control electronics are encompassed in a Full
Authority Digital Electronic Control (FADEC) 30.   The FADEC 30
includes, <u>inter alia</u>, a CPU unit 32, a ROM 34, and a RAM 36.   In
the present embodiment, the FADEC 30 is a 16 bit microcontroller
based on the Intel 8096 microprocessor which was used in previous
generations of Ford engine ECU's.   The fuel is metered and fuel
injection is controlled by the FADEC using the speed-density
method.   The system features distributorless electronic ignition
with double fire capacity.   The FADEC controller is housed in a
sealed enclosure with liquid cooling for high altitude
applications.   The integration of the single input power
controller (SIPC) software was found, in the present embodiment,
to be most efficient as a sub-routine of the FADEC control
program.   The SIPC subroutine receives the relevant power plant
parameters (to be discussed below), performs the SIPC algorithms
(also to be discussed below) and delivers control parameters at
the end of each control cycle.   The FADEC software also controls
engine performance parameters such as injection, spark, mix, etc.
(To be discussed below)

[0027]   Inputs to the FADEC which are used in the SIPC
algorithm include environmental condition inputs such as the
humidity 38, the ambient air pressure 40, and the ambient air
temperature 42.   Input from the single input 44 is provided to
the FADEC 30 through the line 46.

[0028]   The FADEC 30 receives inputs from the various engine
control sensors and provides control outputs to the various
servos as depicted in Fig. 1.   Specifically, the CPU 32 outputs
throttle servo commands to the throttle servo 24, and receives

MAP sensor signals from the MAP sensor 26. The CPU 32 also receives RPM sensor signals from the RPM sensor 8.

[0029]   For controlling the engine performance parameters, the CPU 32 also receives a number of engine status parameters such as Exhaust Gas Temperature (EGT), Cylinder Head Temperature signals (CHTs), Universal Exhaust Gas Oxygen sensor signals (UEGO), Air Charge Temperature signals (ACT), Mass Airflow signals (MAF), and the Exhaust Pressure Signals (PEXH), over a bus 50. In the preferred embodiment, these signals comprise analog signals which may vary between -10 and +10 volts, preferably + or - 5 volts, or as available.

[0030]   The CPU 32 outputs to the prime power source 2 control signals to control the injectors, the spark, and the fuel/air mix, on a bus 52. Again, in the preferred embodiment, the signals are analog signals varying between 0 and 5 volts, or as required. Of course, some or all of the signals provided into and out of the FADEC may be digital signals.

[0031]   A display 54 may be coupled to the FADEC 30 to display the MAP command and/or the generator RPM command. For example, where the system according to the present invention is advisory only and does not actually output commands to change engine and generator performance, displayed MAP and RPM commands may provide the operator with suggested settings for the throttle servo 24.

3.   The Functions

[0032]   Fig. 2 is a functional block diagram showing the
salient features of the SIPC algorithm. Briefly, the FADEC 30
(Fig. 1) receives both the detected environmental conditions and
the commanded power output, and uses these values to access one
or more look-up tables stored in ROM 34 or RAM 36. The look-up
table will provide an RPM command and a MAP command which will
achieve the best output power efficiency for the detected values.
The control algorithm and the look-up tables can be loaded into
an existing computer from a disk. Alternatively, the algorithm
and look-up tables may be provided in a separate computer to
provide the operator with an advisory message rather than
activate the control servos.

[0033]   In more detail, the system constantly monitors the air
data 60, thus knowing the ambient air conditions. This
information is employed in the control mixing algorithm 62 to
select the optimum combination of the engine speed and power (or
load) setting to maximize the output power efficiency achieved,
i.e., maximum efficiency of the combined prime power source and
generator at the detected environmental condition.

[0034]   In operation, the operator commands the desired output
power percentage 64 by using the single input means 44 (Fig. 1).
The control mixing algorithm (preferably, a software subroutine
running in the FADEC 30) transforms the input output power
percentage into a MAP set point to control the engine power/load
controller 66 which, in the proposed embodiment, drives the
throttle servo 24 and the waste gate servo 20 (Fig. 1) to achieve

the desired inlet manifold pressure. On non-turbo charged engines, the throttle servo alone is driven to achieve the desired inlet manifold air pressure. The control algorithm 62 also outputs a generator speed set point (RPM) to the generator speed controller 68 which, in the preferred embodiment, includes gear box servo 6, to control generator speed by actuating the variable speed transmission until the measured speed matches the speed set point.

[0035]   With the desired output power indicated by the input 44, the control mixing algorithm 62 interpolates stored tabulated data (to be discussed below) to determine the MAP and RPM that will maximize output power efficiency at this commanded output power level. Such an interpolation must be handled very carefully, since the optimum MAP and RPM positions may not follow well-defined, linear functions. For example, the optimum conditions may follow irregular boundaries of MAP and RPM.

[0036]   The power output of prime power source 2 is controlled in operation by two primary variables, MAP and RPM. The power output and specific fuel consumption are characterized by testing and/or prediction as functions of MAP and RPM. The generator is characterized by maps of power coefficient and efficiency versus advance ratio, which in turn are functions of RPM, density, and load. The optimization algorithm maximizes the output power efficiency of the combined power generation system.

[0037]   Since the final output of the optimization algorithm is a set of RPM and MAP data versus environmental conditions and output power, these data are stored in the FADEC 30 in look-up

table form and read directly or interpolated to obtain optimum conditions at any environmental condition and output power. In Fig. 5, a constant-output power contour is obtained for the commanded power output and the detected ambient air operating conditions. This contour is projected onto the RPM-MAP plane. For this example, the contour is represented by a series of points describing intersections with the RPM-MAP grid lines. In Fig. 6, the RPM-MAP contour pairs are mapped onto the output power efficiency curve. The output power contour is re-projected onto the thrust efficiency surface, and the result of the operation is a discrete 3D curve. In Fig. 7, the maximum output power efficiency may be constrained for safety and other operating conditions. For example, a safe-operating envelope may be imposed on the projected output power efficiency curve, and the maximum output power efficiency within the constraint is located to yield RPM/MAP setpoints to control the engine and propeller.

[0038]   In more detail, the SIPC described earlier automatically selects MAP and RPM values for a desired power setting, where the MAP and RPM values are predetermined in an off-line optimization process and stored in the FADEC look-up table. This allows the system to get close to the optimum power generation efficiency, except for the effects of uncertainty in the models used in the off-line optimization. The on-line optimization algorithm discussed above fine tunes the base off-line optimization to achieve true optimal power generation efficiency by continually seeking the optimum in real time. This process also corrects for engine/generator wear and part replacements.

[0039]   These control principles apply equally as well in other power generation systems. For example, in the case of a wind turbine, the prime power source 2 is replaced by the wind and a propeller. FIG. 3 (where like items have like numerals) shows a block diagram of a wind turbine system. In this embodiment, a generator 3 is connected to a propeller 4a via a gear box 5. A load 9 is connected to the generator and is comprised of well known electrical transmission means. In this embodiment, environmental conditions are monitored as inputs to controller 30a. A pitch servo 6 is connected to the propeller 4a and is selectably actuated to change the pitch of the propeller blades thereby altering the rotational speed of the propeller. Similar to the previous embodiment, the control algorithm selects the optimum operating speed based on the known performance of the wind turbine and the measured environmental parameters and generates a control signal to the pitch servo 6. Alternatively, the gear box 5 may be a variable speed transmission that may control the operating speed of the generator 3. This gear box control may be in combination with the propeller pitch control or used alone as a means to provide the optimum power generation. A control signal from the controller 30a to the variable speed transmission based on the measured parameters will be provided to select the optimum generator speed for maximum power generation. Still further, it may be advantageous to provide load shedding means 11 connected to the generator 3 to further optimize the operating efficiency of the wind turbine. In this arrangement, CPU 32 would provide a control signal to the load shedding means 11 to change the flow of electrical power in the most efficient

manner based on the measured operating parameters and environmental conditions.

[0040]   Still further, the aforementioned control system may be applied to ground vehicles. Referring to FIG. 4, where like items have like numerals, a ground vehicle is provided with an engine 2a connected to a transmission 5a. The transmission is connected to a plurality of wheels 7 that are in contact with the ground. The engine 2a consumes fuel and propels the vehicle along the ground in accordance with an input command 44 from an operator. Alternatively, the ground vehicle could be unmanned. Optimum operating setpoints for the engine 2a and transmission 5a are determined based on an algorithm stored on the FADEC 30 as previously discussed. This system could easily be applied to hybrid electrical vehicles, fuel cell powered vehicles, battery powered vehicles and vehicles with continuously variable transmissions. Optionally, a control signal may be provided to the transmission 5a to alter the transmission's settings and further provide a means for optimizing the power generation from the engine 2a.

4.   Conclusion

[0041]   The input power controller structure and functions described above can simplify operational tasks and greatly improve engine and power generation performance by selecting the best efficiency for the commanded thrust and detected environmental/operating conditions.

[0042]   The individual components shown in outline are designated by blocks in the Drawings are all well-known in the engine control arts, and their specific construction and operation are not critical to the operation or best mode for carrying out the invention.

[0043]   While the present invention has been described with respect to what is presently considered to be the preferred embodiments, it is to be understood that the invention is not limited to the disclosed embodiments. To the contrary, the invention is intended to cover various modifications and equivalent arrangements included within the spirit and scope of the appended claims. The scope of the following claims is to be accorded the broadest interpretation so as to encompass all such modifications and equivalent structures and functions.